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RESEARCH MEMORANDUM

INVESTIGATION OF SURGE CHARACTERISTICS OF XJ34-WE-32 TURBOJET ENGINE

By John E. McAulay

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

The surge characteristics of the XJ34-WE-32 turbojet engine without the electronic control were investigated in the NACA Lewis altitude wind tunnel. Two methods were used to obtain surge: a rapid approach to surge by fuel steps (transient), and a gradual approach to surge by changing exhaust-nozzle area (quasi steady state).

At any given corrected engine speed between 10,000 and 11,700 rpm, the surge line shifted to lower compressor pressure ratios as altitude was increased from 10,000 to 40,000 feet. The method of approaching surge, whether rapid or slow, had no apparent effect on the location of the surge line at an altitude of 40,000 feet. As altitude increased, the relation between the surge line and the steady-state operating region changed and the stable operating region was increasingly restricted.

Acceleration to rated speed was obtained in the shortest time period at an altitude of 40,000 feet by passing through surge rather than avoiding it, because the margin available for acceleration without surge was small and because the surge was not violent enough to cause a complete breakdown in flow.

INTRODUCTION

The operation of present-day turbojet engines is limited by compressor surge, particularly at high altitudes. Effects of surge on engine operation are difficult to minimize or eliminate because little is known about it. Some of the problems associated with surge are: its origin and means of propagation, the effect of gradual or rapid approach to surge, the influence of other engine components on surge, the effect of Reynolds number (flight conditions) on surge, and the effect that surge has on engine acceleration characteristics. Surge data for a compressor operating as an intergral part of a turbojet engine are given in reference 1.

A limited investigation was conducted at the NACA Lewis laboratory to obtain surge data for the XJ34-WE-32 turbojet engine. The time responses of the following parameters were obtained: fuel flow, indicated airspeed (ram pressure ratio), engine speed, exhaust gas temperature, compressor discharge pressure, and air flow. A rapid approach to surge obtained by a fuel step (transient) and gradual approach to surge obtained by exhaust-nozzle-area change (quasi steady state) were investigated.

Representative data showing the actual time response of several engine and flight variables are presented in the form of oscillograph traces. From these and other traces a surge line is obtained, and the effect of altitude (Reynolds number) on the surge line is shown. The relation between the surge line and the steady-state operating region is also presented.

APPARATUS

Engine and Installation

The XJ34-WE-32 turbojet engine used in this investigation (fig. 1) has a static sea-level thrust rating of 3370 pounds (afterburner inoperative) at an engine speed of 12,500 rpm and a turbine-inlet temperature of 1525° F. At these conditions, the engine air flow is approximately 60 pounds per second. The engine is equipped with an electronic control system which was inoperative during this investigation. The engine has an eleven-stage axial-flow compressor with mixing vanes (figs. 2 and 3), a double annular combustor, a two-stage axial-flow turbine, an afterburner, and a variable-area exhaust nozzle. The mixing vanes are not shown in figure 2 but are located downstream of the outlet guide vanes.

The engine was mounted on a wing in the test section of the altitude wind tunnel (fig. 1). Dry refrigerated air was supplied to the engine from the tunnel make-up air system through a duct connected to the engine inlet. The air flow through the duct was throttled from approximately sea-level pressure to a total pressure at the engine inlet corresponding to the desired flight Mach number at a given altitude.

INSTRUMENTATION

Transient responses of the engine variables were recorded on multiple-channel, direct inking, magnetic-motor oscillographs (fig. 4). The recording unit in combination with its amplifier has a flat frequency response to approximately 100 cycles per second. The

oscillograph chart speed was 2.5 units per second. The sensing devices used for indicating variations in the performance parameters are given in table I.

The oscillograph traces representing air flow and fuel flow actually measure a pressure difference and therefore have a linear relationship with this quantity. On the trace representing air flow, values are given in pounds per square foot absolute and these values may be related to air flow by figure 5 in which air flow is given as a function of pressure difference for several altitudes at a flight Mach number of 0.52. An attempted calibration of fuel flow was unsuccessful; the trends indicated are valid, however.

PROCEDURE

In an earlier phase of the over-all investigation on the XJ34-WE-32 turbojet engine, the presence of surge when operating the engine at steady-state conditions was observed. In order to define the operating conditions causing this surge and its characteristics, the engine operating point first was established at some steady-state condition and then the exhaust nozzle was slowly closed at constant fuel flow, which moved the operating point of the engine toward the region of surge.

The transient surge was observed by imposing various size fuel steps at a constant exhaust-nozzle area of about 190 square inches (projected area). The fuel steps were made by use of two pressure-loaded accumulators to drive a variable-pressure fuel pump. A diaphragm in each accumulator was placed under various pressures, and a solenoid switch made it possible to change the fuel pressure (fuel flow) almost instantaneously by switching from one accumulator to the other.

Fuel steps were introduced at altitudes of 10,000, 20,000, and 40,000 feet and area changes at altitudes of 25,000 and 40,000 feet. All data were obtained at a nominal flight Mach number of 0.52. Complete free-stream ram-pressure recovery was assumed at all flight conditions.

On all the oscillograph traces the variables increase in magnitude as the trace moves in an upward direction on the grid and each trace has a reference value and scale given so that the value of the variable may be computed for any time. At all surge points, values of indicated airspeed, engine speed, compressor discharge pressure, and air flow are given on the oscillograph traces.

RESULTS AND DISCUSSION

Two factors should be considered in analysis of the oscillograph traces. One factor is the effect of pressure pulsations in the make-up air duct on the surge characteristics as compared to the results that would be obtained in flight. These pressure fluctuations were present in the make-up air duct but only after surge had started. Data indicate that the surge point would not be affected by the presence of the duct but the amplitude and frequency of the surge would be influenced by a resonant coupling (reference 2). The other consideration is the effect of extremely high absolute temperatures and rapid temperature changes during a fuel step on the accuracy of the thermocouples measuring exhaust gas temperatures. Although this effect combined with the uneven exhaust gas temperature distribution may lead to error in the temperature measurements, the resulting transient temperature trace is at least indicative of trend.

Oscillograph Traces

Slowly closing the exhaust nozzle at a constant engine fuel flow made it possible to gradually approach the surge that was encountered during steady-state operation. Typical oscillograph traces using this method of approaching surge are shown in figure 6 for altitudes of 25,000 and 40,000 feet. As the exhaust nozzle was closed, the engine speed, air flow, and compressor discharge pressure decreased; the exhaust gas temperature increased and the indicated airspeed remained nearly constant. The surge occurred when the compressor discharge pressure decreased suddenly and began to pulsate. This pressure pulsation was reflected by the pressure devices measuring indicated airspeed and air flow. At the surge point the air flow decreased and the exhaust gas temperature increased (fig. 6(b)). The magnitude of the air flow decrease and the exhaust gas temperature increase depended on the severity of the surge. Opening the exhaust nozzle permitted the engine to resume stable operation.

Typical oscillograph traces showing steps in fuel flow at constant exhaust-nozzle area are shown in figure 7. The results of fuel steps from an initial engine speed of about 6200 rpm at altitudes of 10,000 and 20,000 feet, are presented in figures 7(a) and 7(b). Immediately after the fuel step, the compressor discharge pressure and the exhaust gas temperature increased rapidly; the engine speed and air flow changed slowly because of the inertia of the compressor and turbine. Surge began when the compressor discharge pressure began to pulsate; however, the mean value of compressor discharge pressure continued to increase. Air flow and indicated airspeed reflected the pressure pulsations caused by surge. Because of limitations of the test equipment, it was not possible to maintain a constant indicated airspeed during a

transient and the resulting air flow and indicated airspeed traces are therefore different from those that would exist during similar operation in free flight. During the engine acceleration, the amplitude of the compressor discharge pressure pulsations increased and the mean value of air flow suddenly began to increase rapidly and consequently the exhaust gas temperature decreased. During the particular runs presented, reduction of the fuel flow was necessary to prevent the engine from overspeeding. When the fuel flow was reduced, the compressor stopped surging.

Fuel steps at an altitude of 40,000 feet are shown in figures 7(c) to 7(g). Two fuel steps of different size from an initial engine speed of about 7700 rpm are presented in figures 7(c) and 7(d). In general, the pattern described previously for low altitudes is followed by the smaller of the two fuel steps (fig. 7(c)) except that the surging stopped before rated speed was reached or fuel flow was reduced. The oscillograph traces for the larger step in fuel were similar to those obtained for the smaller one during the initial phase of the acceleration; however, the excessive burning through the turbine and in the tail pipe did not permit the turbine to develop the power necessary to accelerate the engine to rated speed. The engine speed then decreased and surging ceased although the fuel flow had not been reduced.

Progressively larger fuel steps from an initial engine speed of about 11,300 rpm are shown in figures 7(e) to 7(g). For the first two fuel steps the acceleration was accomplished without surging in the compressor. As the size of the fuel step was increased, a surging condition was encountered during which the compressor discharge pressure pulsated with maximum amplitude at the beginning of surge. For the largest fuel step shown (fig. 7(g)), surge occurred as in the previous fuel step, but combustor blow-out occurred before the engine could be accelerated.

Surge Line

The usual method of presenting compressor data is to show the relation among corrected engine speed, compressor pressure ratio, and corrected air flow. Since surge is primarily a function of corrected engine speed and compressor pressure ratio, all the surge points obtained are presented in figure 8, in which the compressor pressure ratio at which surge occurred is plotted as a function of corrected engine speed for a range of altitudes. Both a rapid and slow approach to surge were made at an altitude of 40,000 feet and within the experimental accuracy of the data the method of approaching surge had no effect on the location of the surge line. The range of engine speeds over which surge was encountered in the slow approach was limited, however. Because the surge data obtained at low altitudes were obtained at low engine speeds

only, the altitude effect on the surge line cannot be determined from this data. Further effects of altitude on the surge line may be shown by consideration of the surge data available in conjunction with the steady-state operating lines.

The surge lines shown in figure 8 and the steady-state operating lines for altitudes of 10,000, 25,000, and 40,000 feet are presented in figure 9. The closed-nozzle steady-state operating lines for altitudes 10,000 and 25,000 feet lie above the surge line for 40,000 feet at corrected engine speeds greater than 10,000 rpm. The surge lines for altitudes of 10,000 and 20,000 feet must lie above the closed-nozzle steady-state operating lines for these two altitudes because of the satisfactory steady-state operation that was obtained; consequently, the surge lines for low altitudes must be located at higher compressor pressure ratios than for high altitudes, at least between corrected engine speeds of 10,000 to 11,700 rpm. This effect of altitude on the location of the surge line occurs at a given corrected engine speed. The effect of altitude on the compressor pressure ratio at which surge occurs for a given corrected air flow would be somewhat different from the altitude effect illustrated in figure 9 because of the change in corrected air flow due to the Reynolds number effect. This effect would be evident in a more conventional plot of compressor pressure ratio against corrected air flow. Sufficient data to completely evaluate this effect were not, however, available.

Steady-state data with the closed exhaust nozzle could not be obtained at an altitude of 40,000 feet above an engine speed of about 10,700 rpm, because of surge. At an altitude of 10,000 feet, surge points could not be obtained by slowly closing the exhaust nozzle, because surge was so mild that no definite surge point could be established. Apparently as altitude increased the relation between the steady-state operating region and the surge line changed, at least in the region in which surge could be encountered by slowly closing the exhaust nozzle. This change in the relative positions of the surge line and steady-state operating region increasingly restricted the stable operating region as altitude was increased. Engine operating experience indicated that the severity of the surge obtained by closing the exhaust nozzle also increased as altitude was increased.

The compressor surge line and compressor map with lines of constant corrected engine speed and exhaust-nozzle area are presented for an altitude of 40,000 feet in figure 10. These data show the region of steady-state operation which was eliminated by surge and also the small margin between the surge line and the steady-state operating lines available for acceleration without surge.

Acceleration Characteristics

The time required to obtain rated engine speed as a function of the size of fuel step is presented in figure 11 for an altitude of 40,000 feet and a flight Mach number of 0.52 at a projected exhaust-nozzle area of 190 square inches. As previously stated, a calibration of the fuel-flow trace was not obtained. It is possible, however, to obtain from the oscillograph traces a number which is proportional to the size of the fuel step. These values are used on the abscissa in figure 11 and are proportional by an unknown constant to the increase in fuel flow. These data show that at a given initial engine speed a fuel step that is large enough to fall to the right of the curve indicated as surge will cause surge. For example, at low initial engine speeds (below 10,000 rpm) surge will be obtained if a single fuel step is used to obtain rated speed even though the size of the fuel step is just large enough to obtain rated speed. Acceleration to rated speed was made within the shortest time period at an altitude of 40,000 feet by passing through surge rather than avoiding it, because the margin available for acceleration was small and because the surge was not violent enough to cause a complete breakdown in the flow. Because a complete breakdown in flow did not occur, the high exhaust gas temperatures that existed during surge were encountered for only a very short time.

The data indicate that within the range of initial engine speeds investigated, approximately the same size fuel step will permit the engine to reach rated engine speed in the minimum time, independent of initial engine speed. As the fuel steps increase in size, a point is reached at which the combustor is unable to produce the proper burning to give the turbine the available power that is required for acceleration and acceleration time increases very rapidly.

Similar data are not available at other flight conditions and exhaust-nozzle areas. However, the effect of decreasing altitude and increasing flight Mach number at a given exhaust-nozzle area for any given initial engine speed would be to widen the range of fuel steps which could be used to obtain rated speed and decrease the minimum time required to obtain rated speed. Increasing the exhaust-nozzle area for a given flight condition and fuel step size for any initial engine speed decreases the time required to obtain rated speed.

There was some indication that the vibrations and high temperatures caused by surge could result in structural damage to the engine if repeated many times. This structural damage was evidenced by cracking of the supporting struts for the inner cone of the tail-pipe diffuser.

SUMMARY OF RESULTS

From a brief investigation of the surge characteristics of the XJ34-WE-32 turbojet engine, the following results were obtained:

1. Increasing the altitude from 10,000 feet to 40,000 feet at a given corrected engine speed resulted in shifting the surge line to lower compressor pressure ratios between corrected engine speeds of 10,000 and 11,700 rpm.

2. Within the accuracy of the data either a rapid or slow approach to surge at an altitude of 40,000 feet had no effect in the location of the surge line. However, only a limited range of data were obtained by a slow approach to surge.

3. As altitude was increased, the relation between the surge line and the steady-state operating region changed and the stable operating region was increasingly restricted.

4. Acceleration to rated speed was made in the shortest time period at an altitude of 40,000 feet by passing through surge rather than avoiding it, because the margin available for acceleration without surge was small and because the surge was not violent enough to cause a complete breakdown in the flow.

5. For an exhaust-nozzle area of about 190 square inches at an altitude of 40,000 feet, a given size fuel step will permit the engine to reach rated speed in the minimum time or nearly so regardless of the initial engine speed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 17, 1951

REFERENCES

1. Conrad, E. William, Bloomer, Harry E., and Sobolewski, Adam E.: Altitude Operational Characteristics of a Prototype Model of the J47D (RX1-1 and RX1-3) Turbojet Engines with Integrated Electronic Control. NACA RM E51E08.

2. Bullock, Robert O., Wilcox, Ward W., and Moses, Jason J.: Experimental and Theoretical Studies of Surging in Continuous-Flow Compressors. NACA Rep. 861, 1946. (Formerly NACA TN 1213.)

TABLE I - SENSING DEVICES FOR PERFORMANCE PARAMETER VARIATIONS

Performance parameter	Transient instrumentation		Steady-state instrumentation
	Sensor	Frequency response range (cycles/sec)	
Engine speed	Direct-current tachometer	0-5	Chronometric tachometer
Compressor discharge pressure	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level pressure	Three rakes with five total-head tubes per rake
Indicated airspeed (total pressure at engine inlet)		0-10 at sea-level pressure	Airspeed indicator
Fuel flow (pressure drop through orifice)		Indeterminent	Rotometer
Air flow (velocity pressure at engine inlet)		0-10 at sea-level pressure	
Exhaust gas temperature	Unshielded loop thermocouples (five in series)	0-1 at sea-level mass flow	Five rakes with six thermocouples per rake

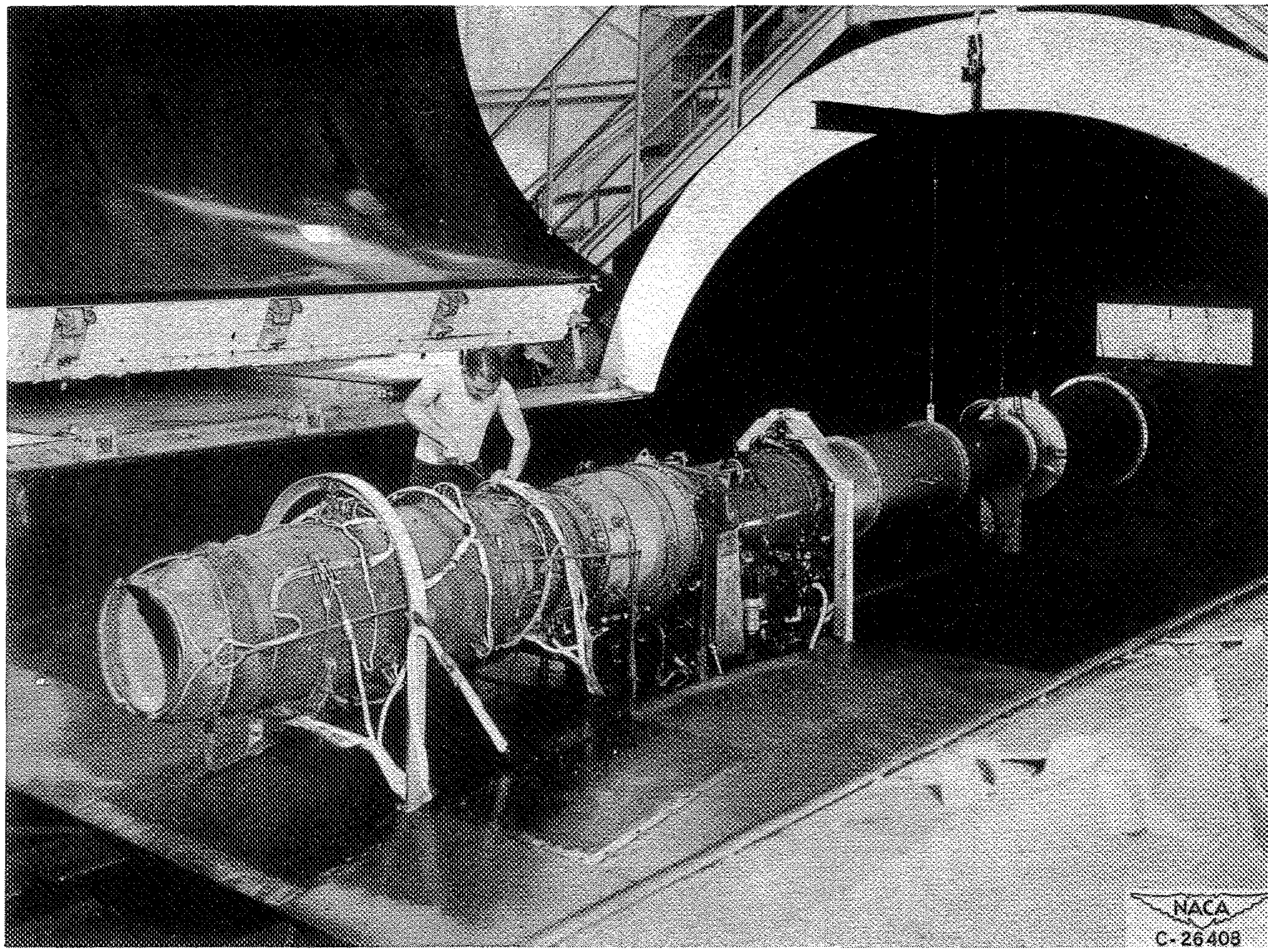


Figure 1. - Installation of XJ34-WE-32 turbojet engine in altitude wind tunnel.

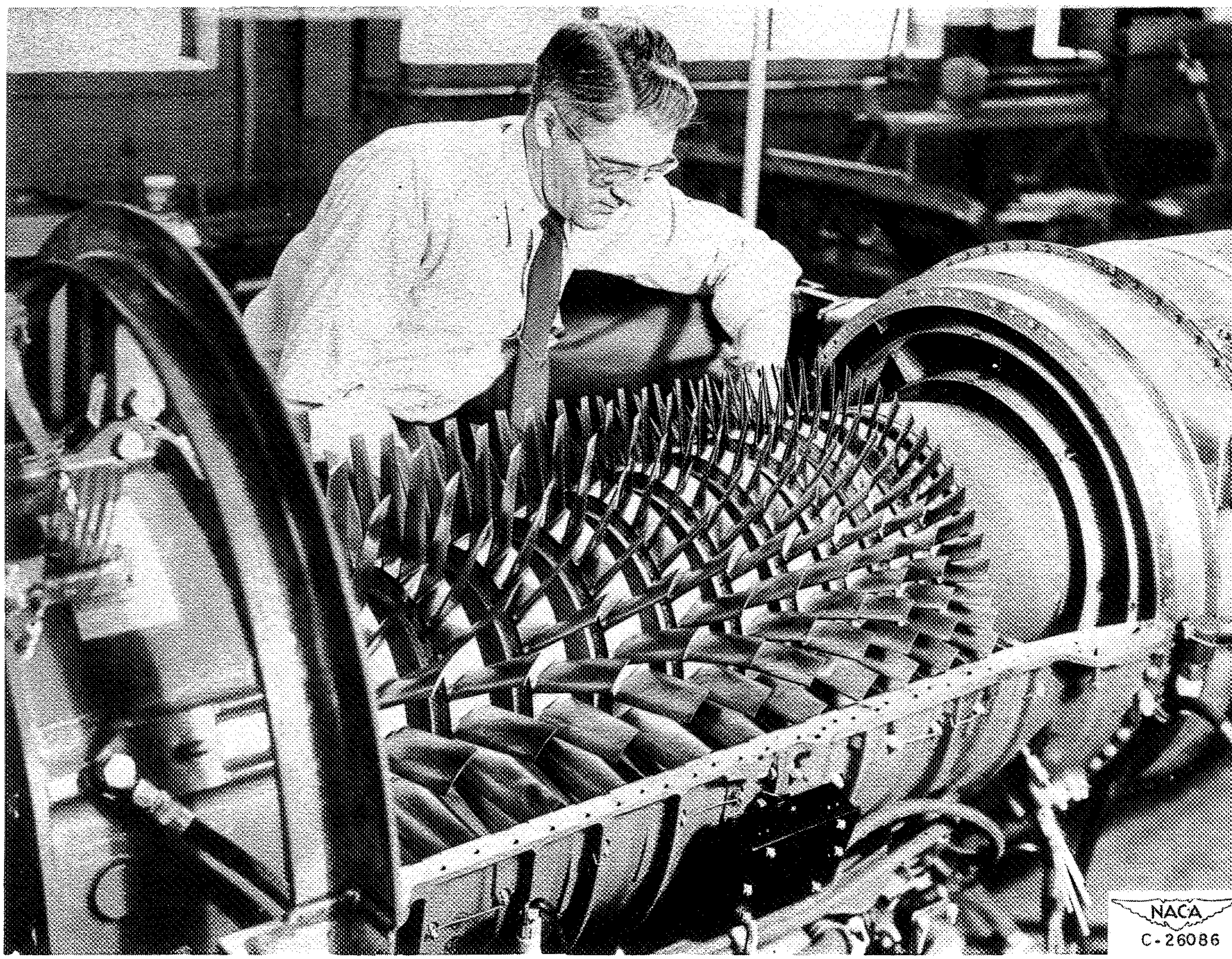


Figure 2. - Compressor without mixer.

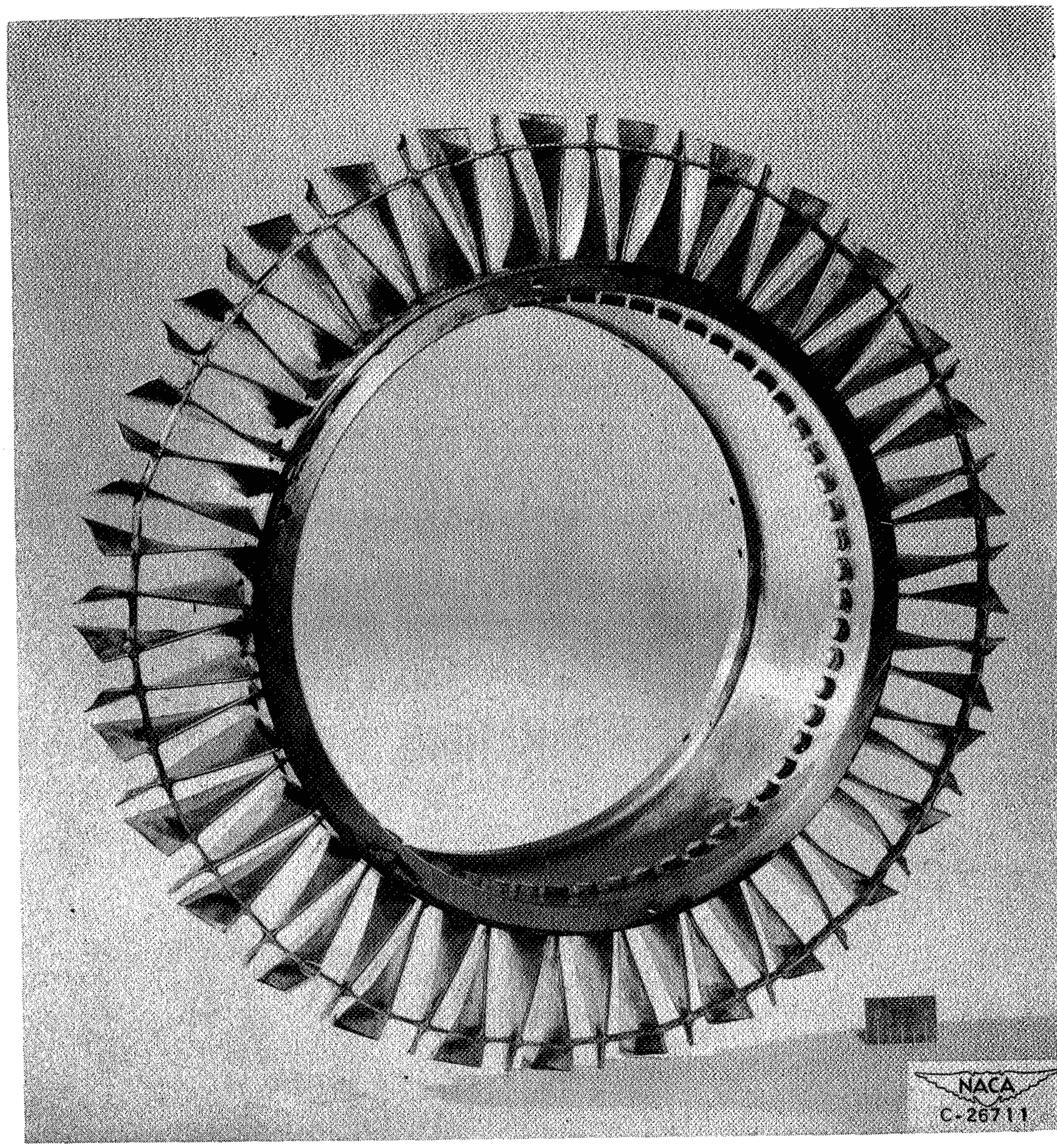


Figure 3. - Mixing vanes.

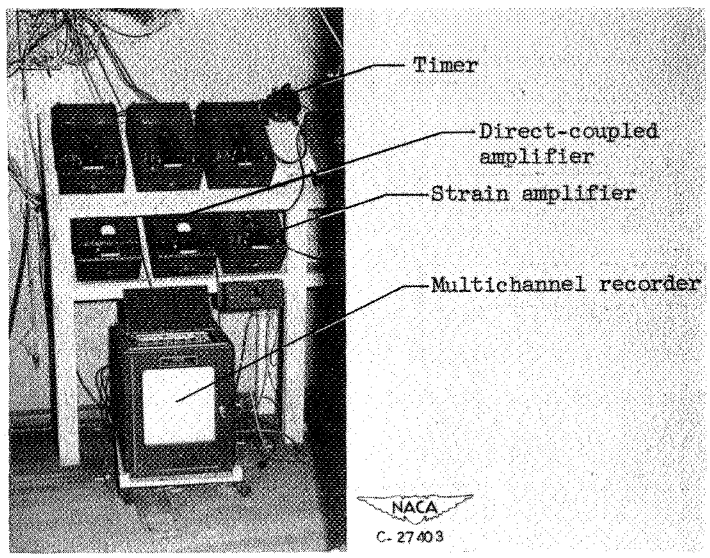


Figure 4. - Recording oscillograph with six amplifiers.

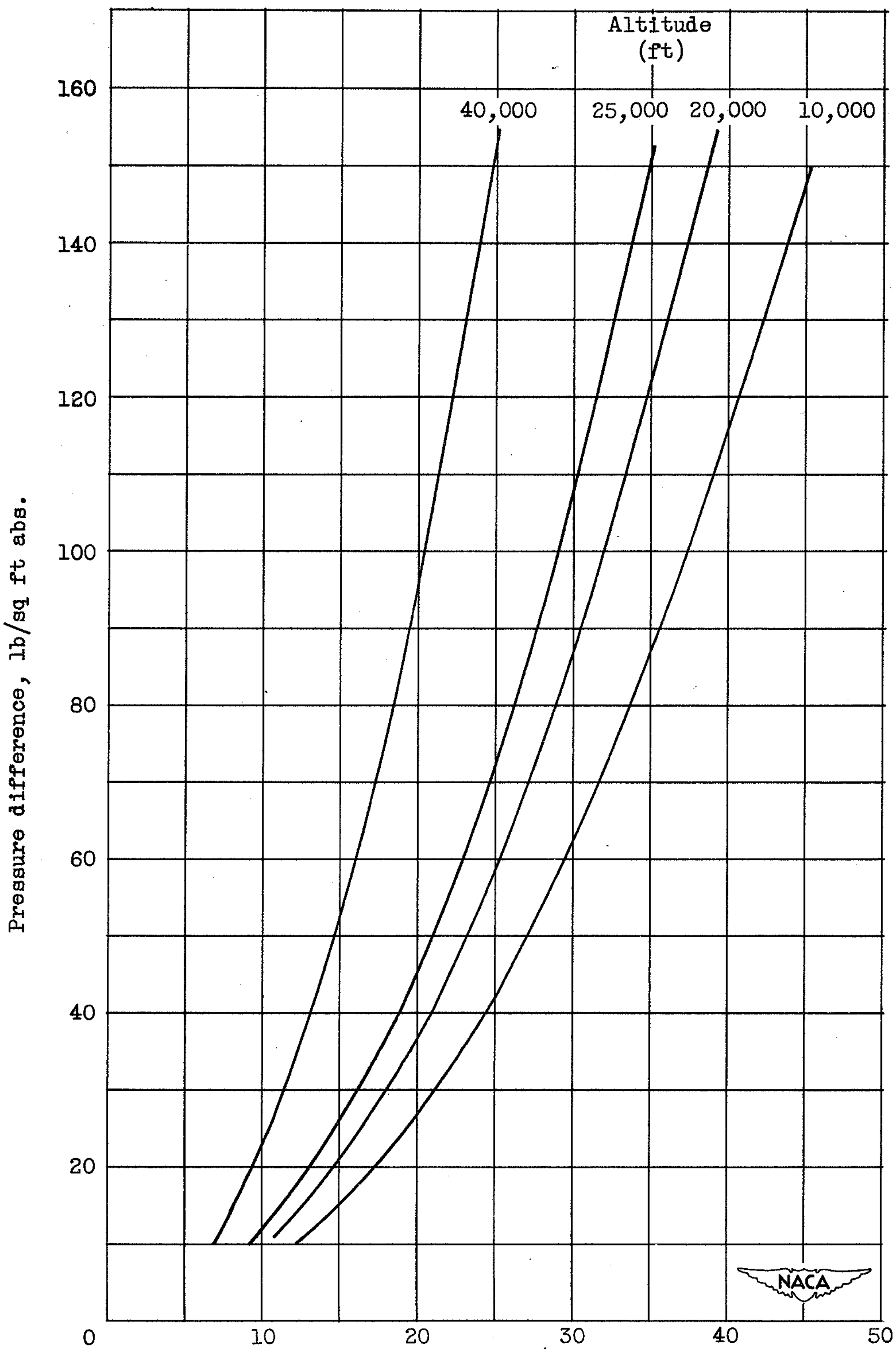
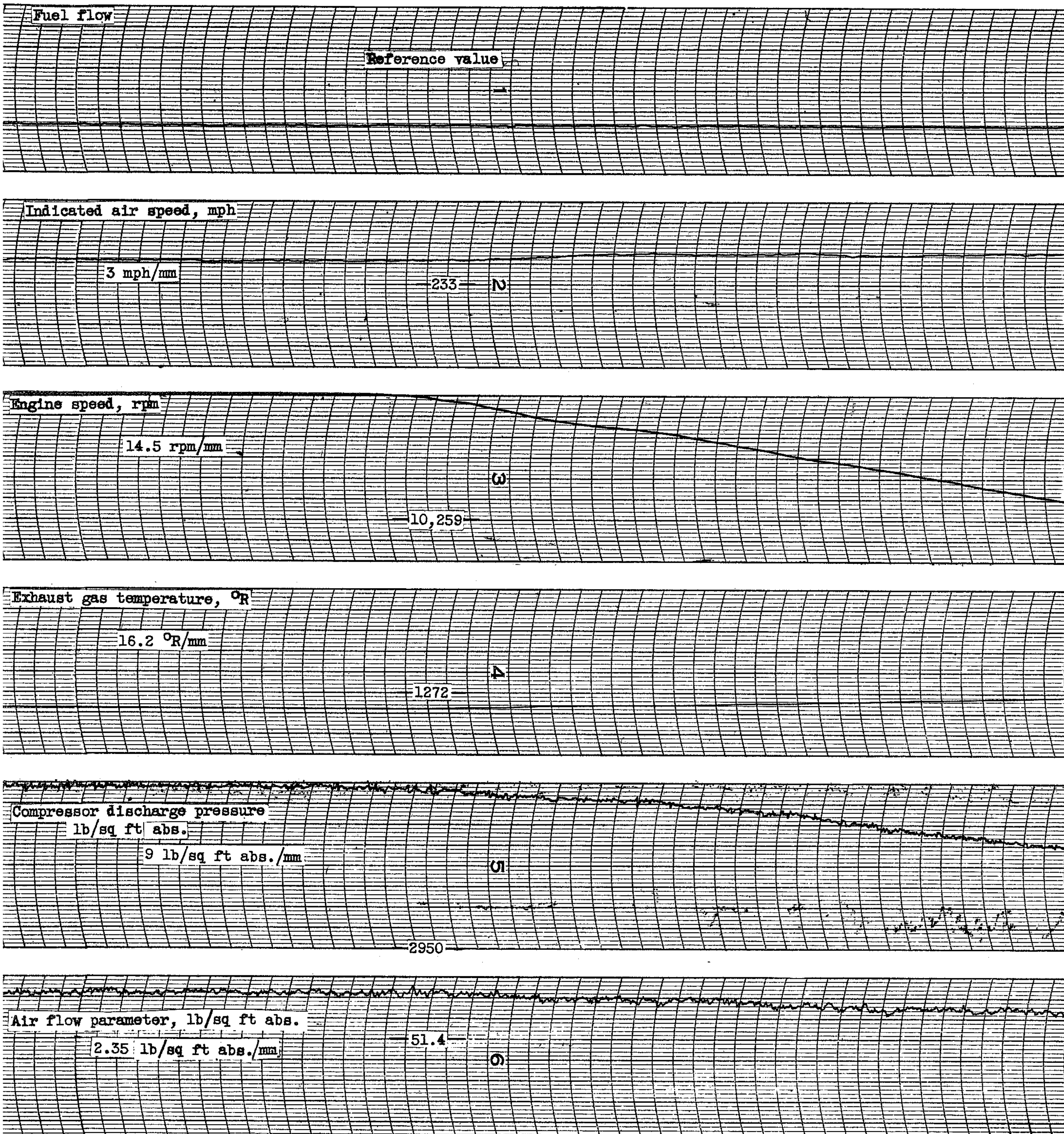
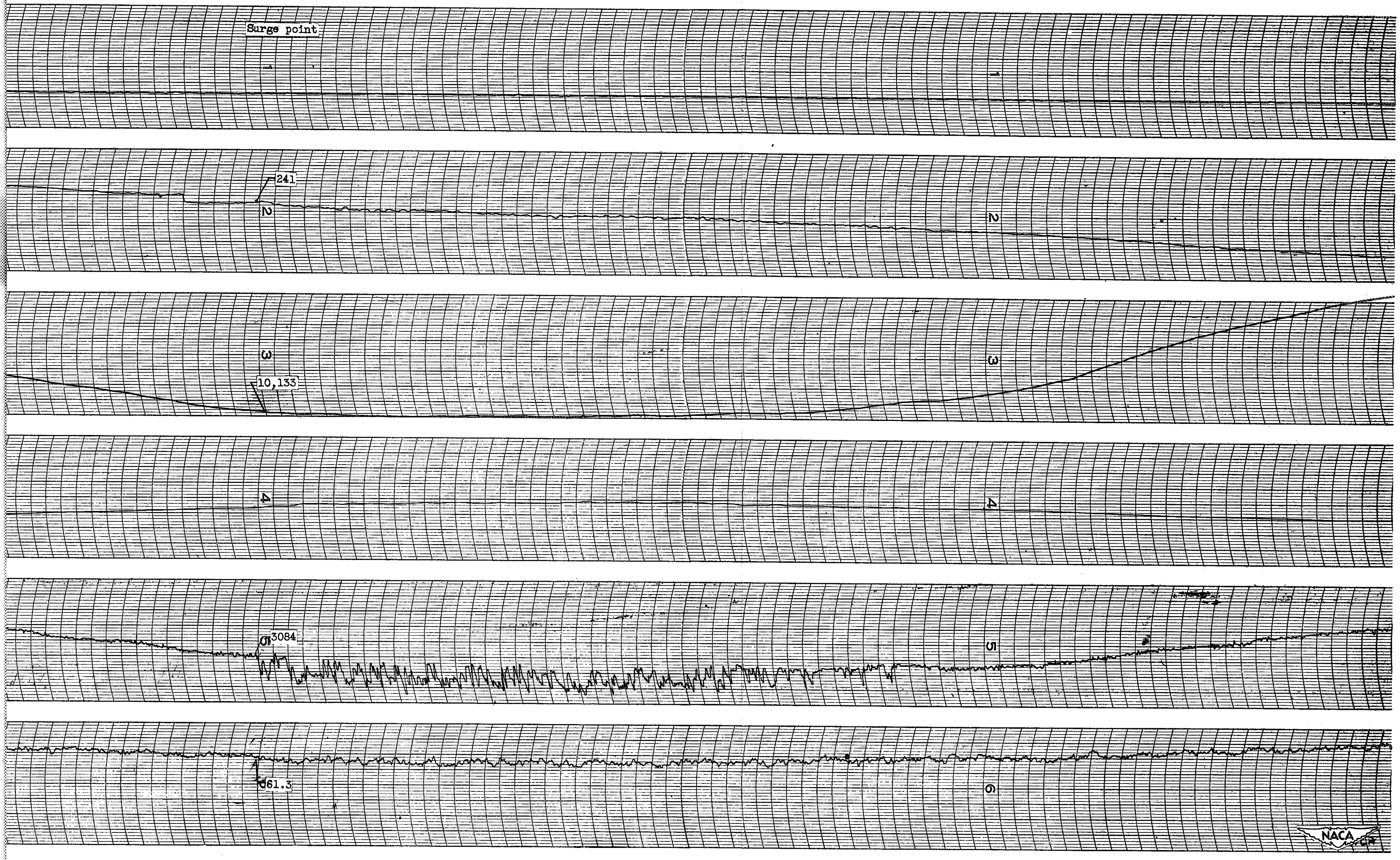


Figure 5. - Variations of pressure difference with air flow at a flight Mach number of 0.52 for various altitudes.


Fuel flow
Reference value
1
Indicated air speed, mph
3 mph/mm
233
2
Engine speed, rpm
14.5 rpm/mm
3
10,259
Exhaust gas temperature, °R
16.2 °R/mm
4
1272
Compressor discharge pressure
lb/sq ft abs.
9 lb/sq ft abs./mm
5
2950
Air flow parameter, lb/sq ft abs.
51.4
2.35 lb/sq ft abs./mm
6



(a) Altitude, 25,000 feet.

re 6. - Change in exhaust-nozzle area which resulted in surge. Flight Mach number, 0.52.

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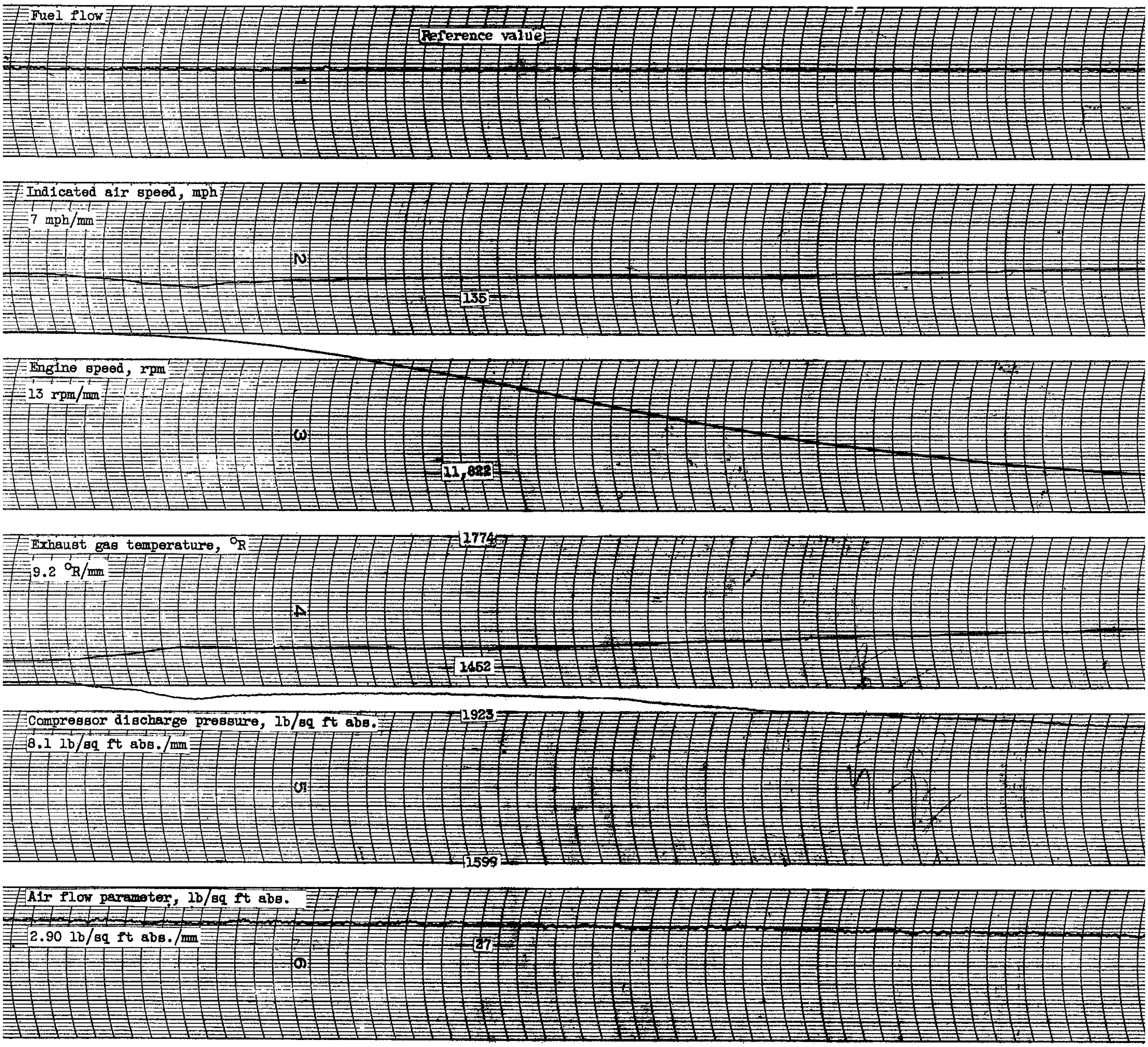
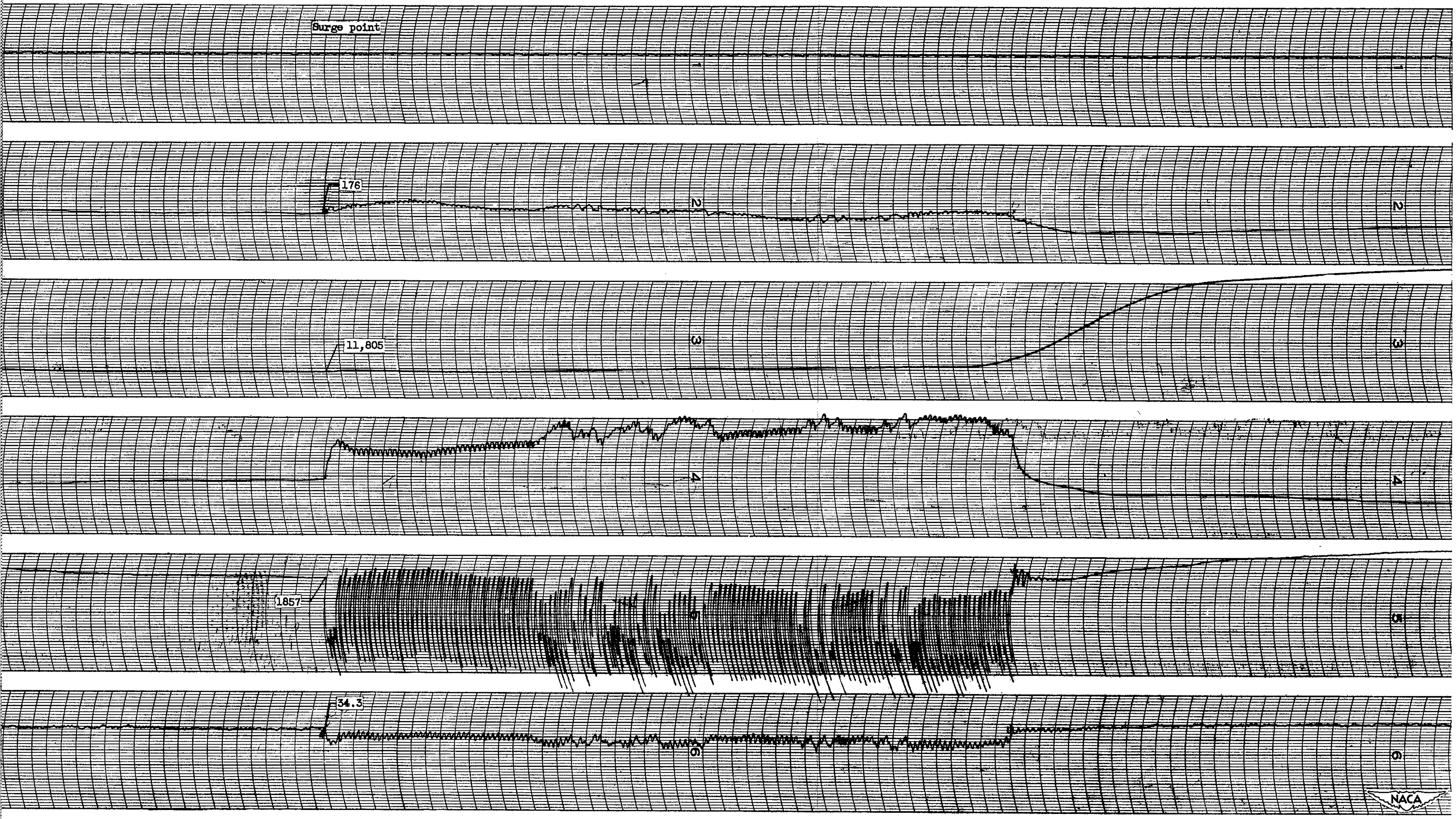

Fuel flow
Reference value
Indicated air speed, mph
7 mph/mm
2
135
Engine speed, rpm
13 rpm/mm
3
11,822
Exhaust gas temperature, °R
9.2 °R/mm
4
1774
1452
Compressor discharge pressure, lb/sq ft abs.
8.1 lb/sq ft abs./mm
5
1923
1599
Air flow parameter, lb/sq ft abs.
2.90 lb/sq ft abs./mm
6
27

Figure



(b) Altitude, 40,000 feet.

ncluded. Change in exhaust-nozzle area which resulted in surge. Flight Mach number, 0.52.

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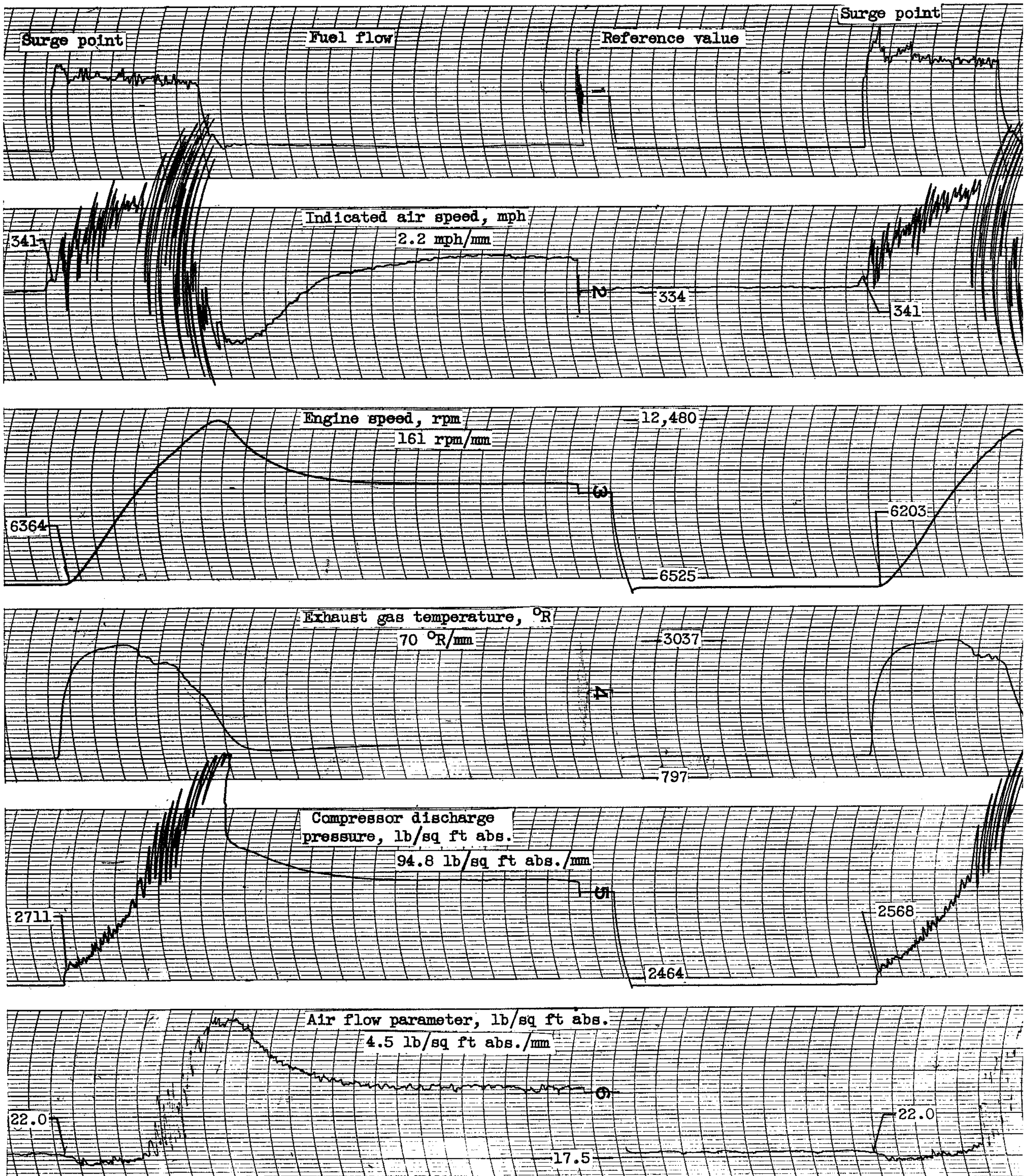

(a) Successful accelerations with surge. Altitude, 10,000 feet. Initial engine speed, 6250

Figure 7. - Fuel flow steps. Flight Mach number, 0.52.

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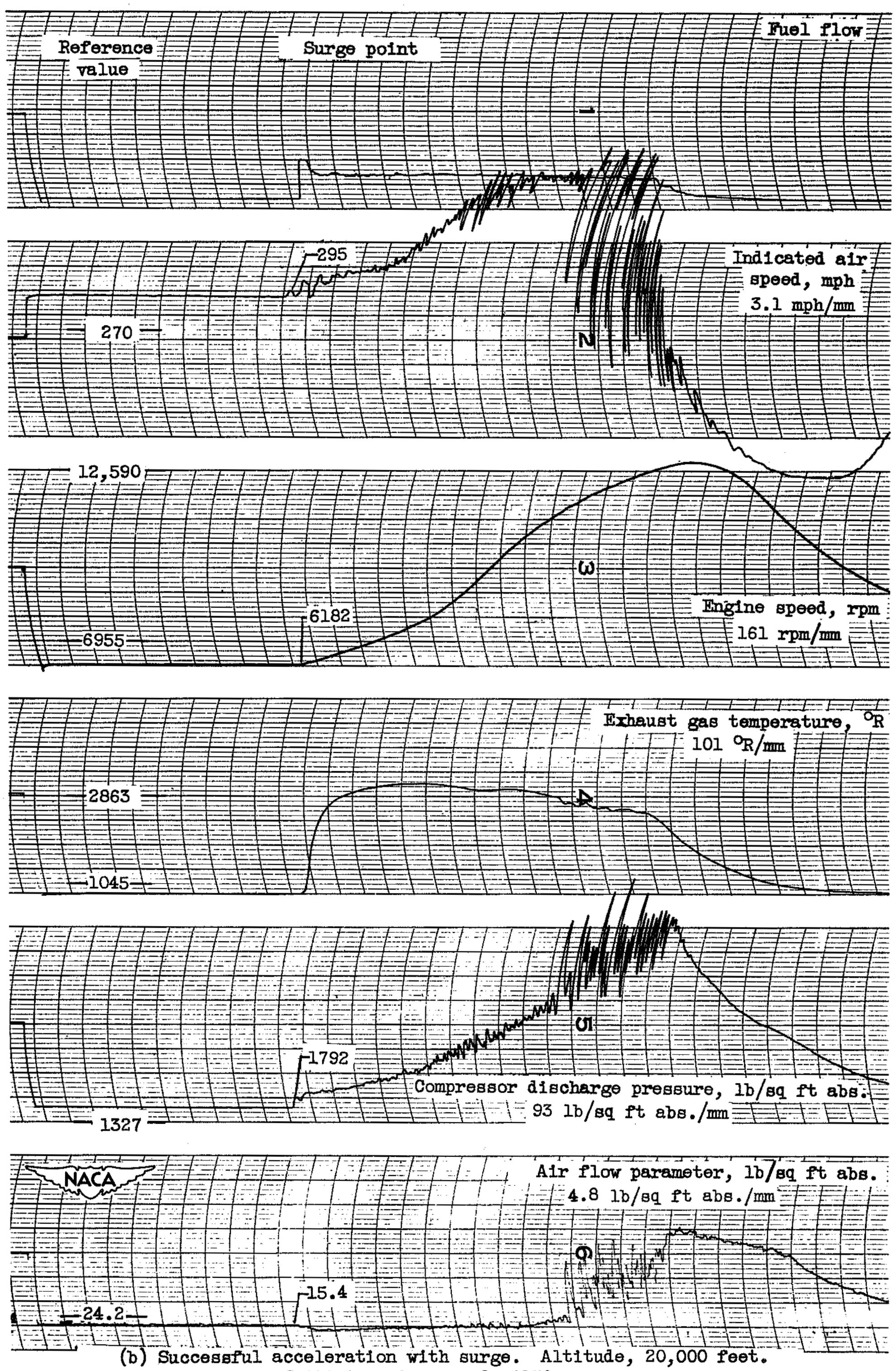

(b) Successful acceleration with surge. Altitude, 20,000 feet.
Initial engine speed, 6150 rpm.

Figure 7. - Continued. Fuel flow steps. Flight Mach number, 0.52.

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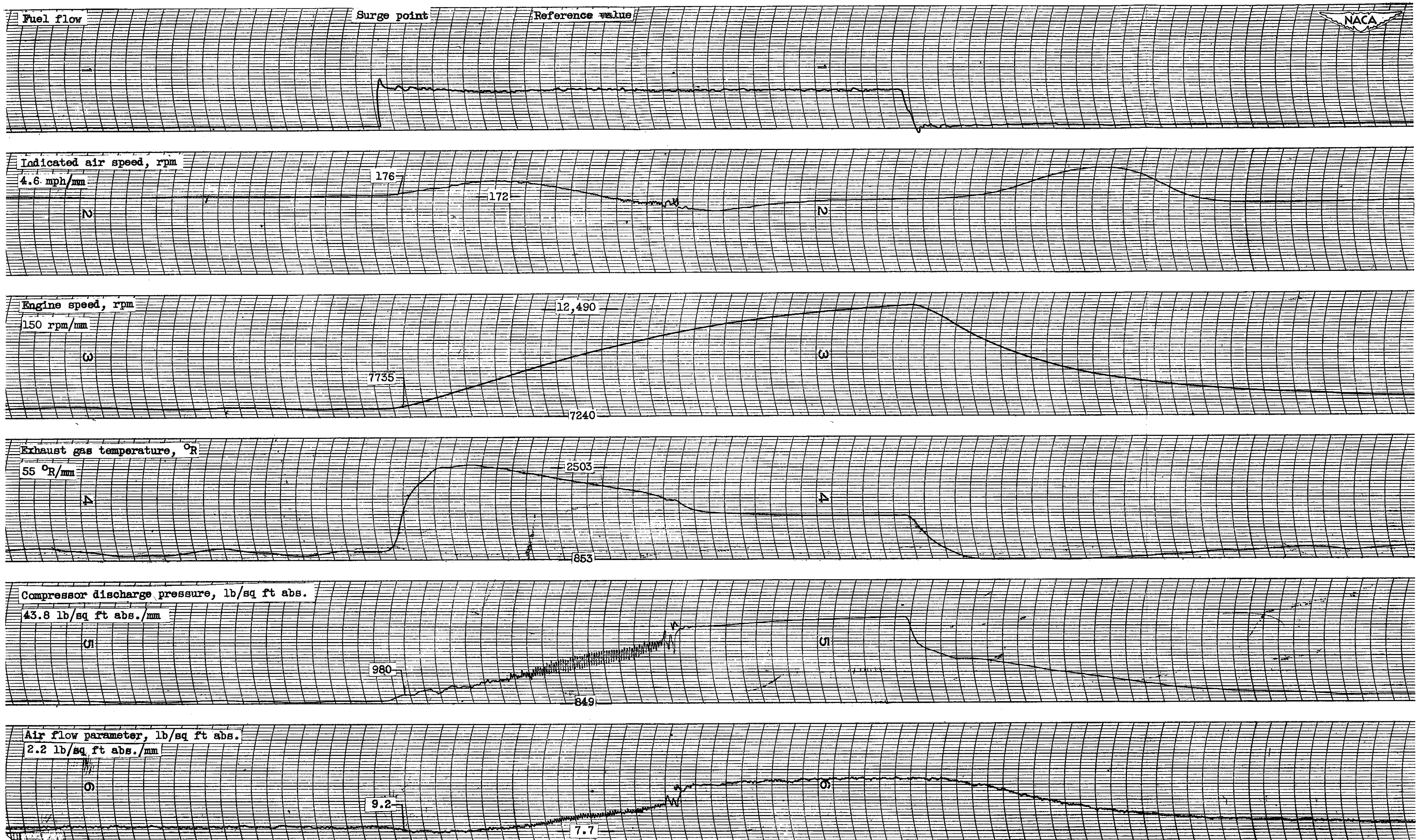

(c) Successful acceleration with surge. Altitude, 40,000 feet. Initial engine speed, 7700 rpm.

Figure 7. - Continued. Fuel flow steps. Flight Mach number, 0.52.

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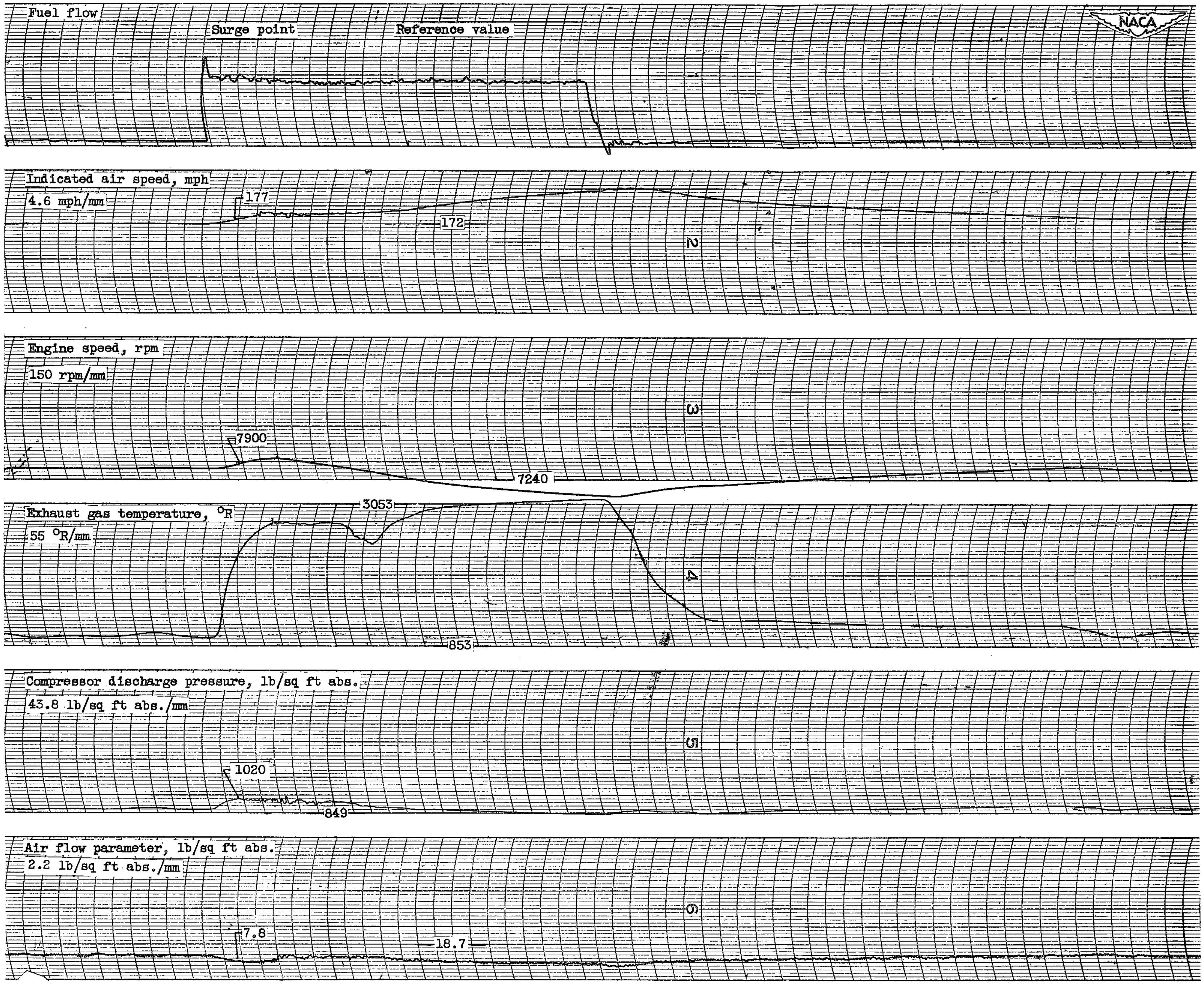

(d) Unsuccessful acceleration with surge. Altitude, 40,000 feet. Initial engine speed, 7700 rpm.

Figure 7. - Continued. Fuel flow steps. Flight Mach number, 0.52.

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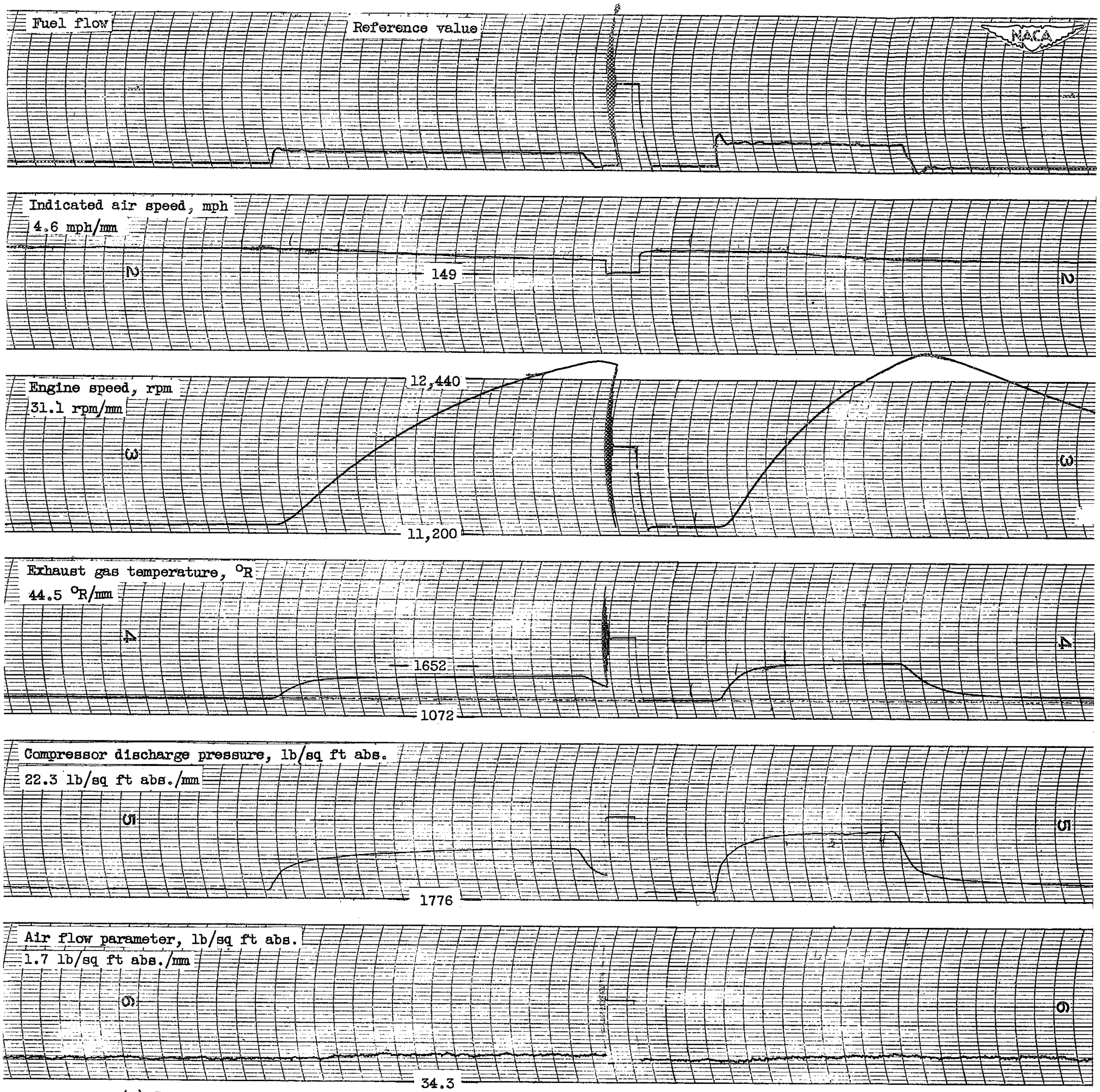

(e) Successful accelerations without surge. Altitude, 40,000 feet. Initial engine speed, 11,260 rpm.

Figure 7. - Continued. Fuel flow steps. Flight Mach number, 0.52.

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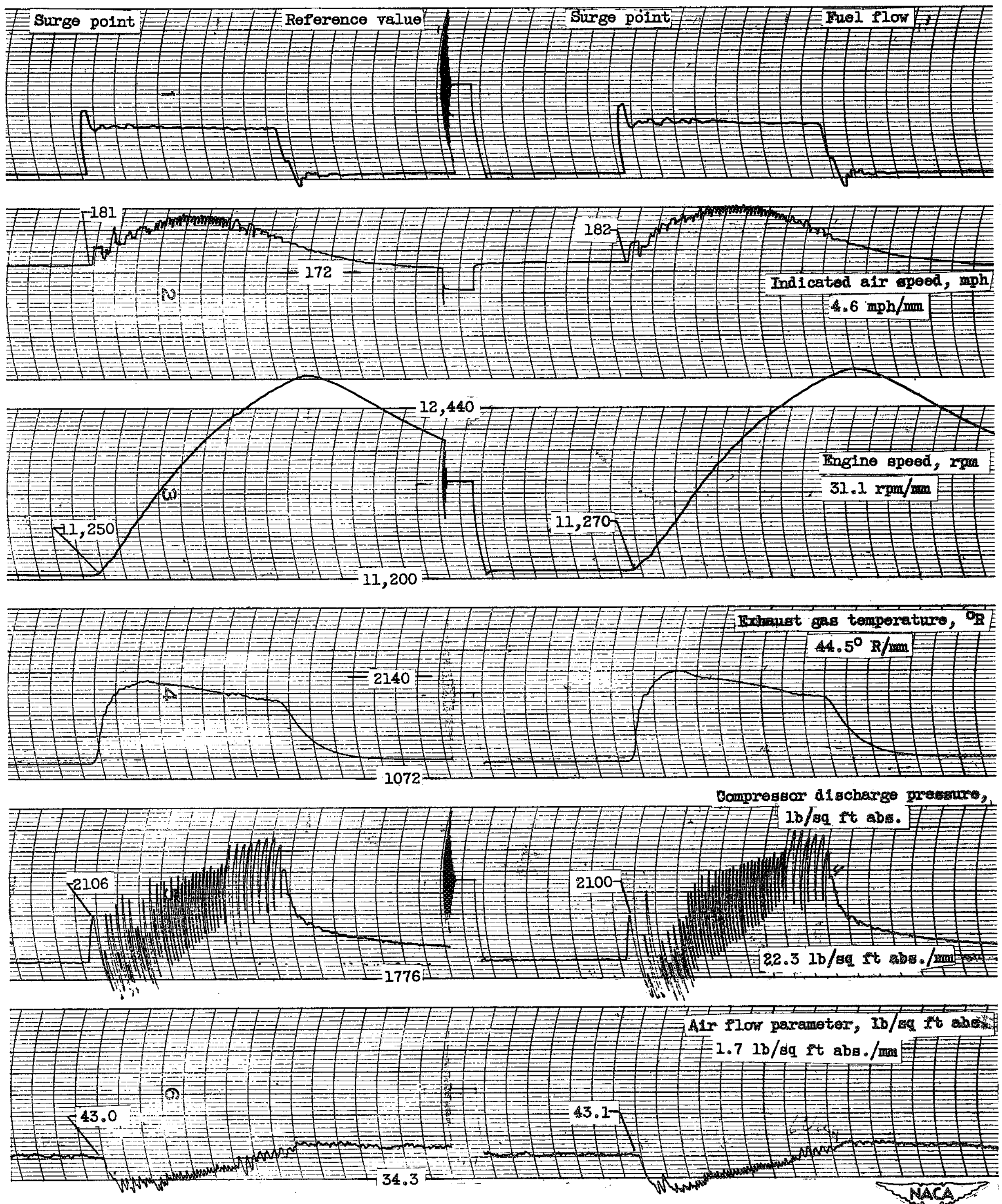

(f) Successful accelerations with surge. Altitude, 40,000 feet. Initial engine speed, 11,250 rpm.

Figure 7. - Continued. Fuel flow steps. Flight Mach number, 0.52.

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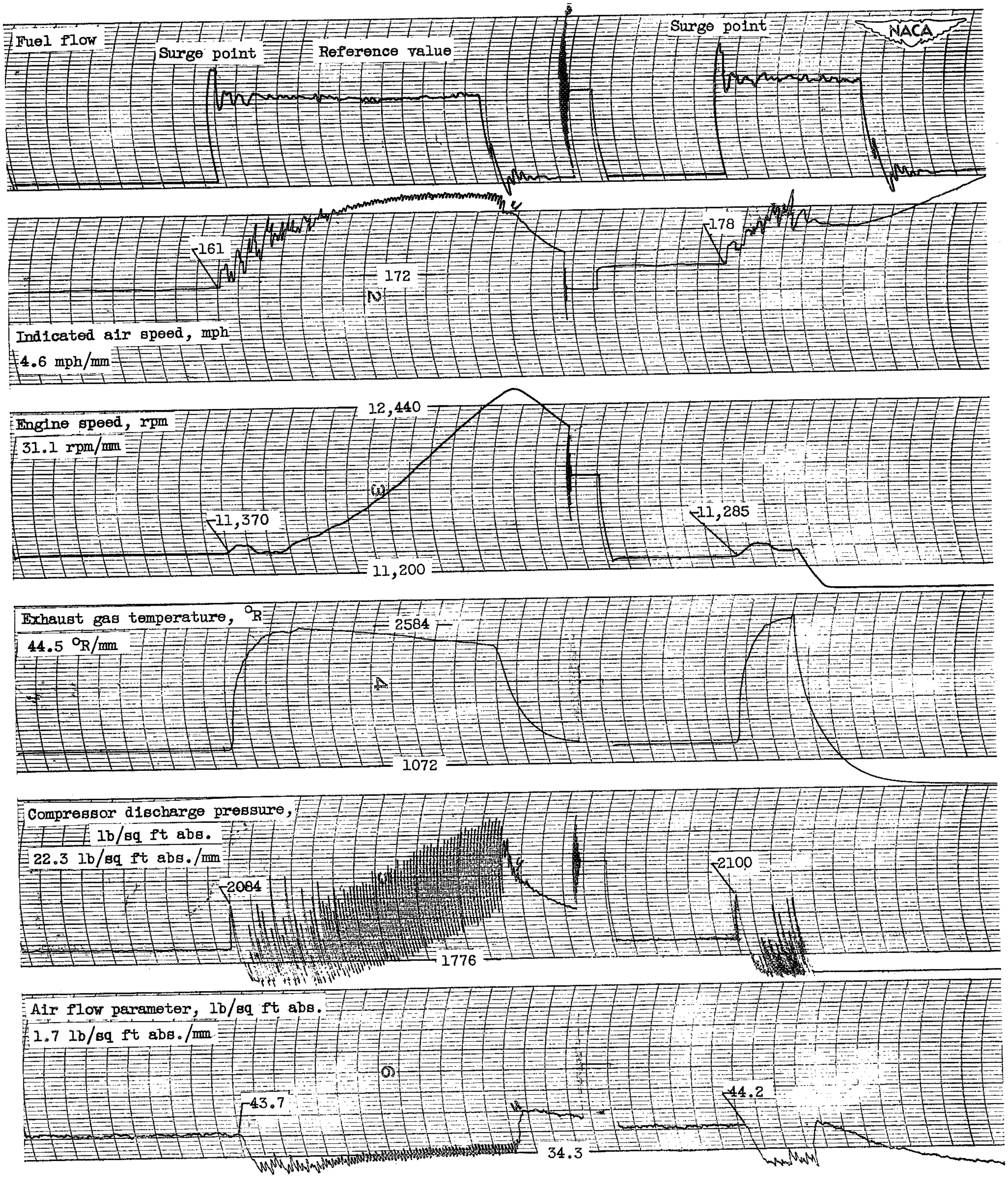

(g) Successful and unsuccessful accelerations with surge. Altitude, 40,000 feet. Initial engine speed, 11,300 rpm.

Figure 7. - Concluded. Fuel flow steps. Flight Mach number, 0.52.

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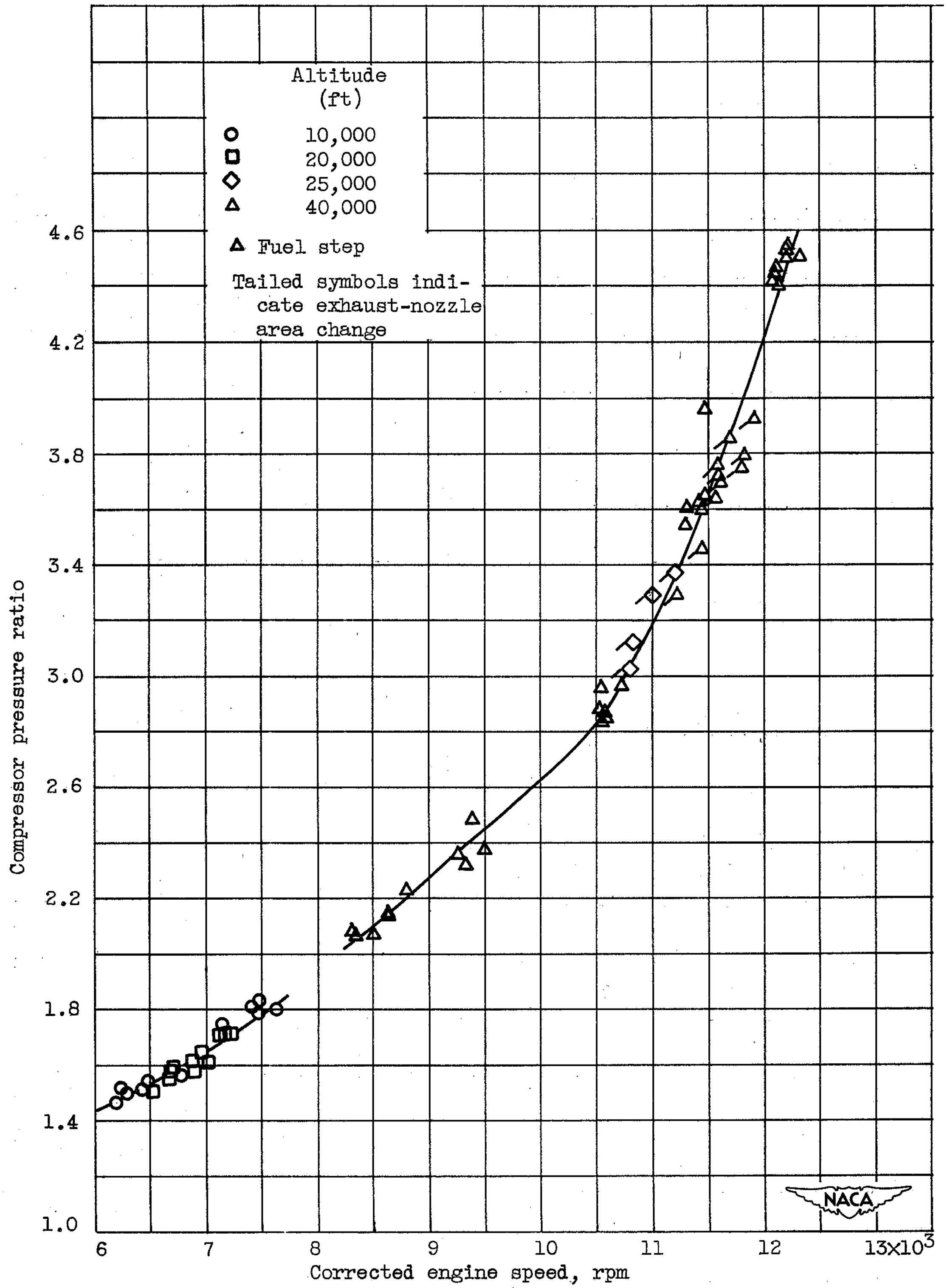

Figure 8. - Compressor surge line at a flight Mach number of 0.52.

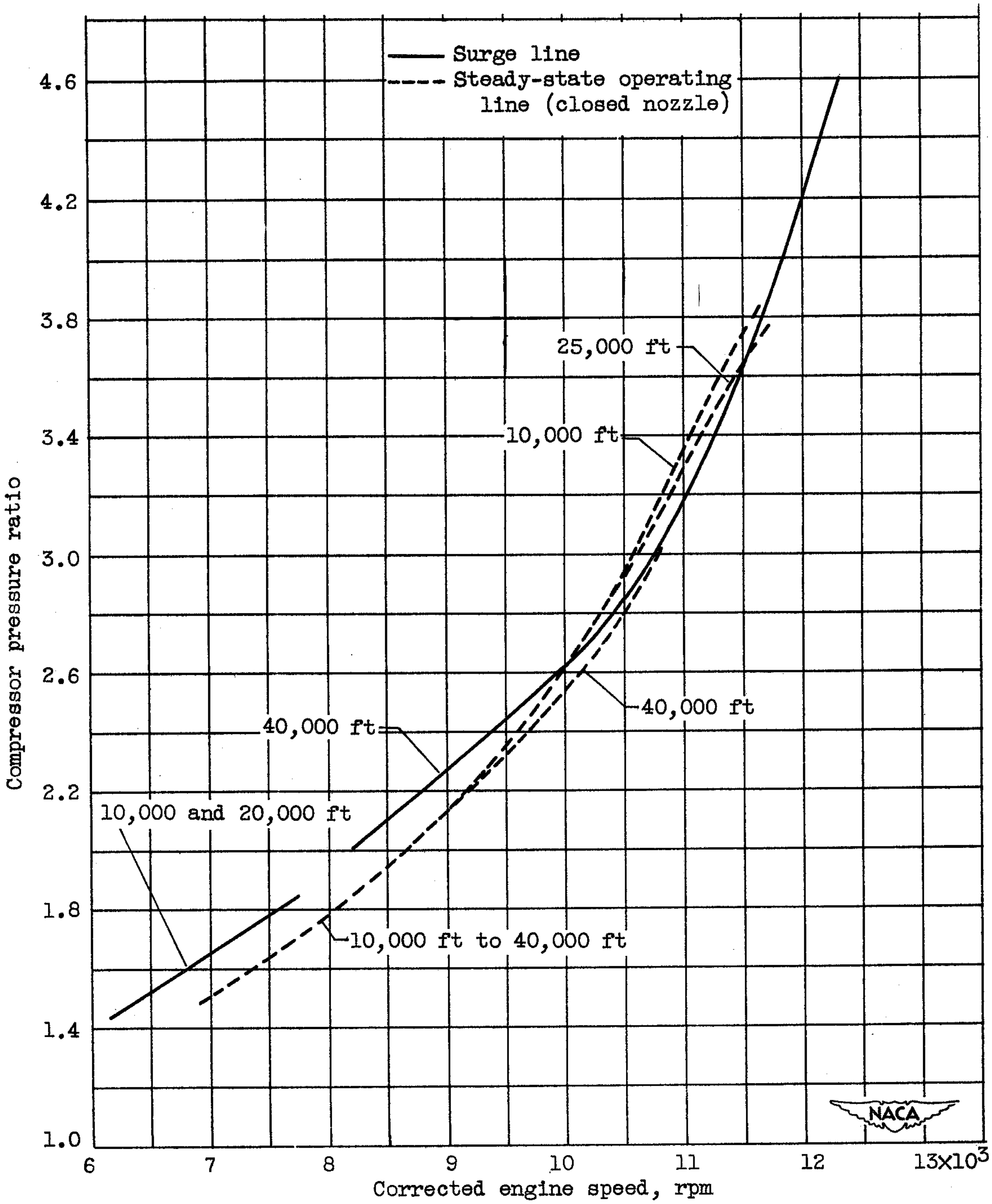

Figure 9. - Relation of surge line to steady-state operating line. Flight Mach number, 0.52.

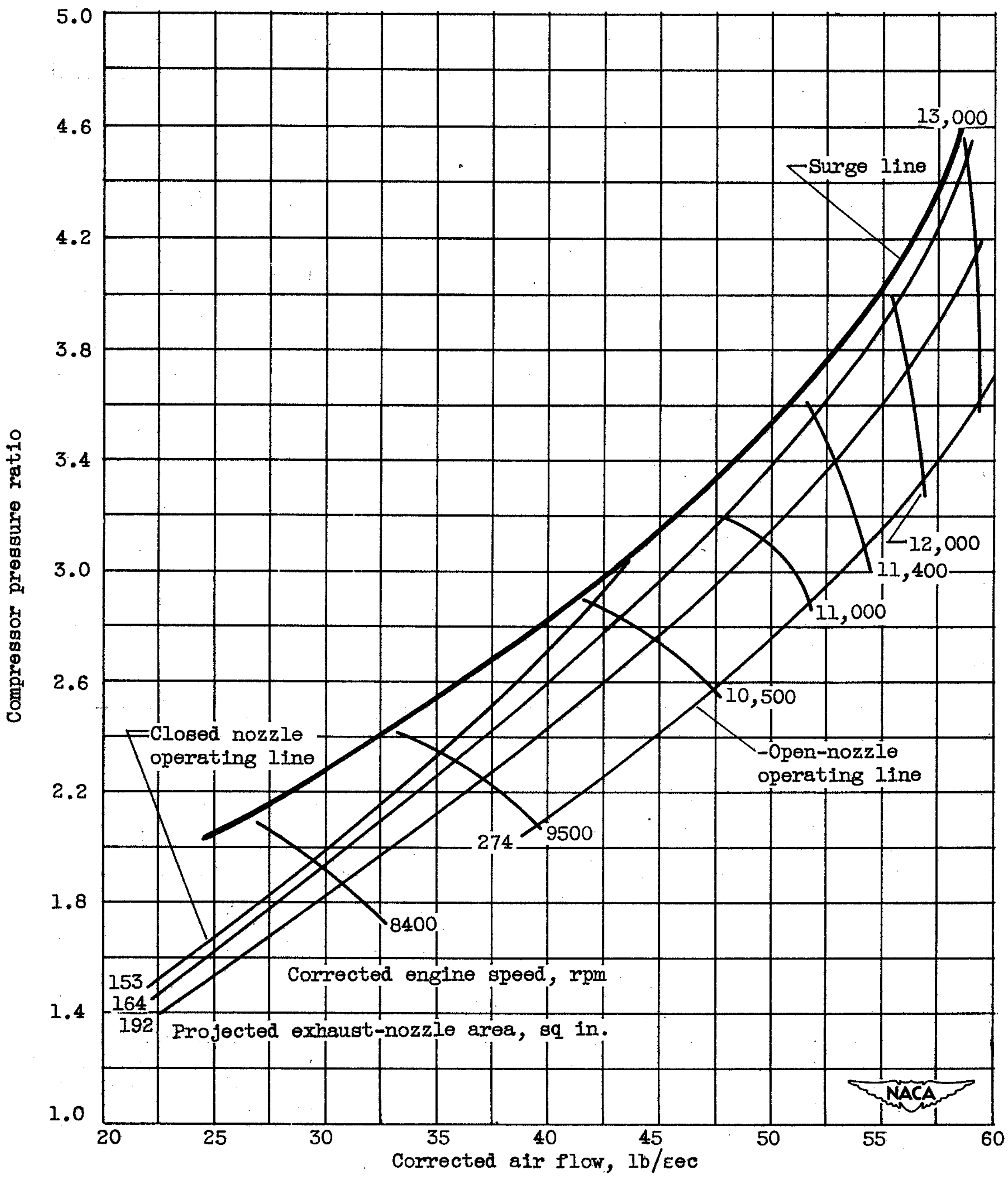

Figure 10. - Compressor surge line and map. Altitude, 40,000 feet. Flight Mach number, 0.52.

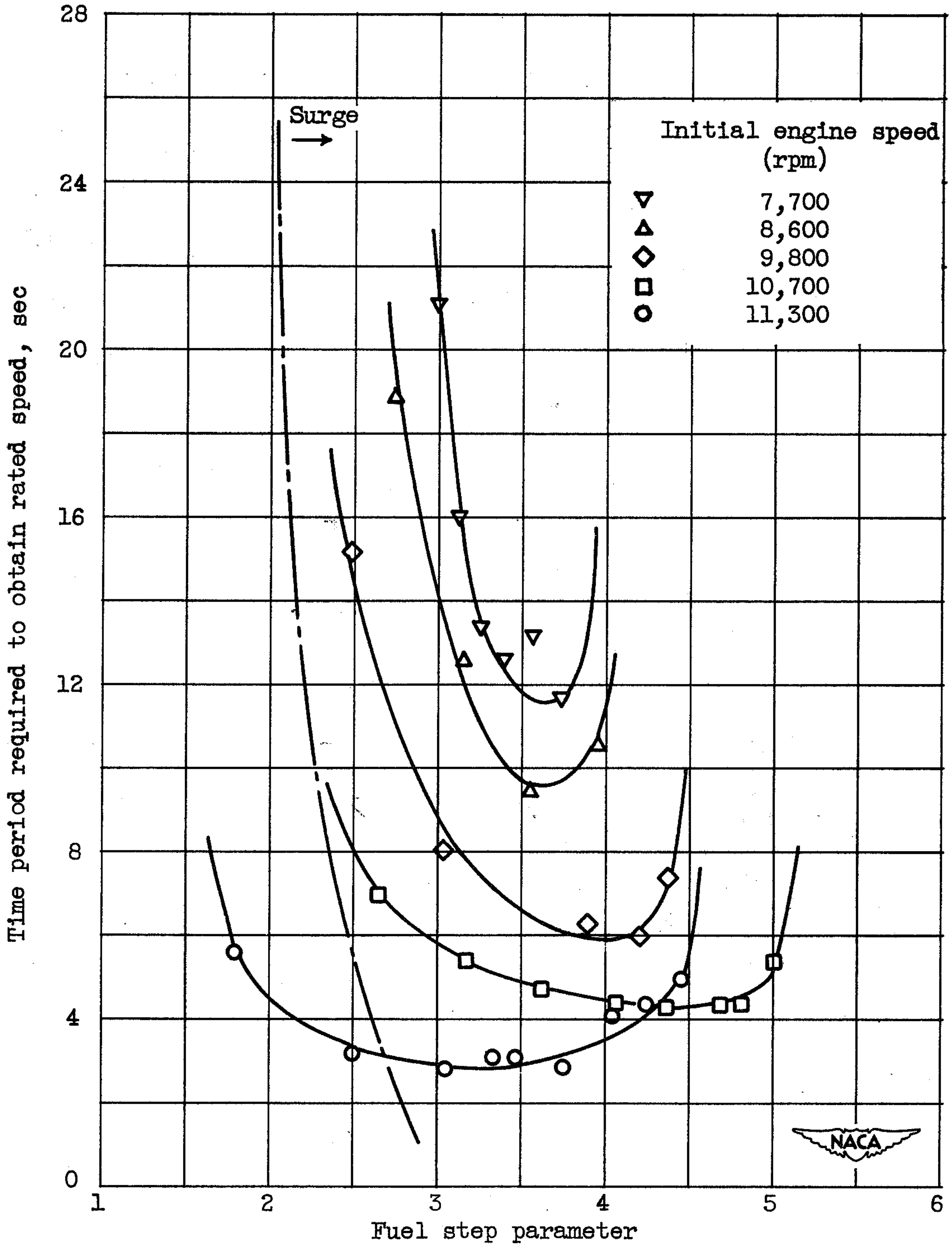

Figure 11. - Variation of time period required to obtain rated speed with fuel step. Altitude, 40,000 feet. Flight Mach number, 0.52. Exhaust-nozzle area, 190 square inches.

NACA RM E51J02 CO Restriction/Classification Cancelled

INVESTIGATION OF SURGE CHARACTERISTICS OF

XJ34-WE-32 TURBOJET ENGINE

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Restriction/Classification Cancelled 'IAL

Engines, Turbojet 3.1.3

Compressors - Axial Flow 3.6.1.1

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Abstract

Surge characteristics of the XJ34-WE-32 turbojet engine were determined over a range of altitudes.

Several typical oscillograph traces during which surge occurred are presented. The effect of altitude on the surge line and its relation to the steady-state operating region are shown.